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Improving Construction Work Zone Safety Using Technology: A Systematic Review of Applicable Technologies

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Review Article

Improving construction work zone safety using technology: A systematic review of applicable technologies

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HIGHLIGHTS

- 147 work zone safety technology (WZST) related articles from 1995 to 2018 are reviewed.
- WZSTs were classified into three categories: speed reduction systems, intrusion prevention and warning systems, and human-machine-interaction detection systems.
- 68% of WZST related studies focused on speed reduction systems.
- The most evaluated WZSTs are changeable message systems (CMSs), speed enforcement technologies, and warning lights.
- Future WZST studies should focus on developing decision-making tools, automated technologies, and benefit-cost models.

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ABSTRACT

Once considered conventional, the construction industry is gradually increasing its reliance on innovations such as the application of technologies in safety management. Given the growing literature on technology applications in safety management and the varying opinions on the utility of applied technologies, a systematic review that streamlines findings from past studies is indispensable to construction stakeholders. Although a number of review studies are available in the building construction sector, the level of fragmentation and uniqueness within the construction industry necessitates a review study specifically targeting the heavy civil sector. In response, the present study applies a three-step approach to identify and review articles pertinent to the safety of highway construction work zones. The factors considered include the number of publications per year, publication locations, and technology types. In addition, the present study proposes to broadly group work zone safety technologies (WZSTs) into three categories based on their primary purpose: speed reduction systems, intrusion prevention and warning systems, and human-machine-interaction detection systems. Key findings include WZST research trends, application of smart work zone systems, and the potential relationship between WZSTs and fatalities. The paper ends with the identification of six additional

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research areas aimed at deepening the understanding of technology's role in highway safety management. The trend analysis and an in-depth discussion of each technology category alongside the identified research gaps will provide a substantial informative body of knowledge that both benefits current practitioners and directs researchers towards potential future studies.

1. Introduction

In 2017, the heavy construction sector in the United States (US) contributed approximately $237 billion to the US economy, employing about 1 million people, which represented 0.8% of the working population, yet accounted for 3% of the fatalities in the industry (BLS, 2018; US Census Bureau, 2019; US Department of Commerce, 2019). Data from the Bureau of Labor Statistics (BLS) show that of the 152 fatalities in total in the US heavy civil sector in 2017, 132 were worker fatalities at road construction sites (BLS, 2018). Constant exposure to safety risks and hazards is inevitable in highway construction and maintenance projects, largely due to the need for work to be undertaken near live traffic. The Federal Highway Administration (FHWA) reported that a work zone fatality occurs every 15 h in the US, while injuries associated with work zone accidents take place every 16 min (FHWA, 2018). These statistics indicate that one out of every five fatalities in work zones is a construction worker. Regardless of the high number of fatalities, recent reports envisage a steady growth in infrastructure investment in the coming years (FMI, 2018). With an increased number of highway projects, workers will be more exposed to safety risks, invariably escalating the risk of accidents, injuries, and fatalities. Therefore, it is paramount that adequate interventions be implemented to effectively mitigate the increased safety risk.

Several interventions have been introduced to protect workers and drivers from the increasing number of casualties linked to highway maintenance and construction. Programs such as the National Work Zone Awareness Week and Turning Point have been implemented by FHWA and the American Road and Transportation Builders Association (ARTBA) to help reduce the work zone fatality rate. Although post-program assessments indicated that work zone fatalities have decreased, annual motorist-induced deaths have remained relatively stagnant (Sant, 2014). To this effect, the use of technology in work zones has been encouraged and implemented in several states across the US as a tool to reduce fatalities. These technologies can be defined as methods, systems, or devices that are products of the application of scientific knowledge for practical purposes (COBUILD, 2005). While the application of technology to improve worker safety is considered one vital component in construction safety management (Zhou et al., 2013), both building and heavy civil sectors have consistently lagged behind most industries in terms of technology adoption, implementation, and diffusion (Gonzalez de Santos et al., 2008; Zhou et al., 2013).

Previous studies have found some benefits associated with implementing safety technologies in work zones, yet a degree of uncertainty still exists regarding the extended usefulness of safety technologies. Apart from the "inherent conservatism" towards such technologies, the lack of consensus in reported research findings is a significant barrier (Xue et al., 2014). Other factors have been identified as possible reasons for slow adoption such as the inability to quantify the benefits of the technologies using direct measure of effectiveness (MOE), nonexistent or negative benefit-cost/return on investment, and interference with work procedure (Fyhrie, 2016; Mitropoulos and Tatum, 2000; Nnaji et al., 2019).

Therefore, it is essential to synthesize and document findings from past studies on the effectiveness of work zone technologies to provide a comprehensive and concise resource that details the usefulness/inadequacy of safety technologies in construction work zones. Apart from the review on work zone speed reduction measure, e.g., Debnath et al. (2012), no review study has focused on identifying and assessing the impact of safety technologies on highway safety (construction workers and motorist). The limited review studies on safety technology concentrated solely on building construction projects (Zhou et al., 2013, 2015). Although available statistics indicates that fatalities occurs at a high rate (per year) in the building construction and heavy civil construction subsectors (196 and 152, respectively) (BLS, 2018), 88% of identified safety management-related studies are focused on building projects (Zhou et al., 2015). As a result, this study on highway construction safety technologies is essential to fill this research gap.

Given the sparsity of review literature on safety technology and its lopsidedness toward building construction, there is a need for a comprehensive study that establishes the impact of existing highway work zone safety technologies. In response, the objective of the present study is to synthesize previous evaluation studies on work zone safety technologies (WZSTs). WZSTs are technologies utilized by state department of transportation (DOT) and contractors to improve the safety of motorist and workers within the work zone. This synthesis will provide a concise reference on the state of WZST for highway construction stakeholders. In addition, the literature review will provide

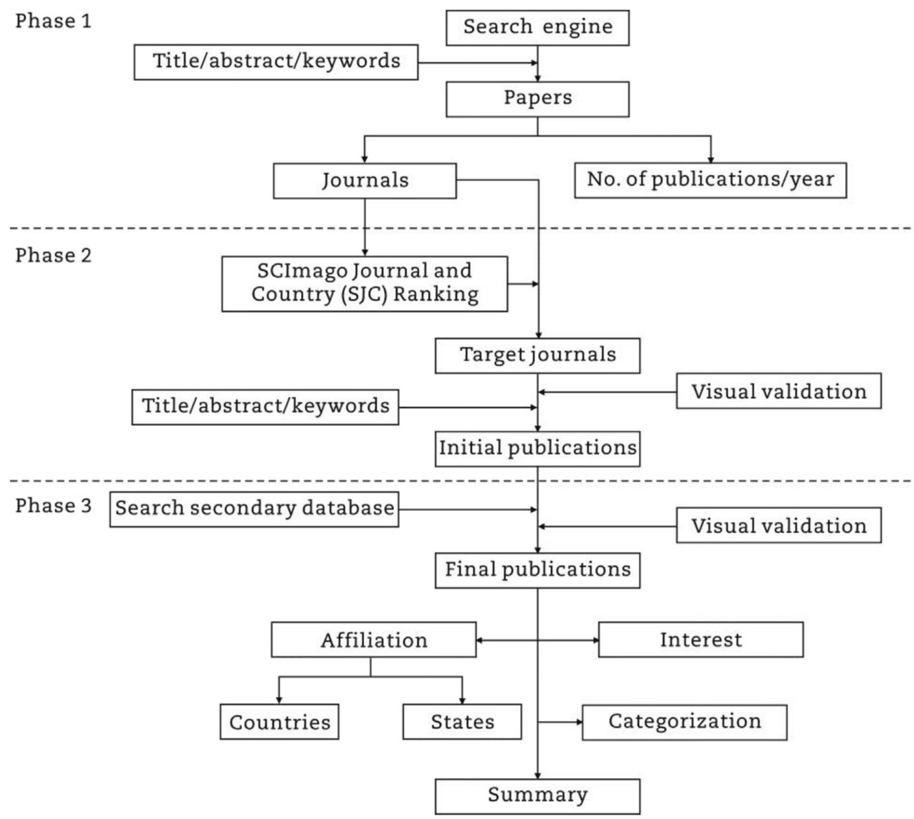


Fig. 1 – Research methodology.

directions for future research by identifying gaps in the present literature.

The balance of this paper is structured as follows. (1) The methodology section explains a study design for this systematic review. (2) The data collection section presents a three-phase framework for collecting useful data. (3) The data analysis section analyzes trends and technology classifications. (4) The discussion section presents an in-depth discussion of the impact of evaluated work zone technologies, and the last two sections discuss research findings, identify gaps in knowledge, and provide conclusions, recommendations, and research limitations.

2. Methodology

In order to produce a coherent insight on a specific topic, a systematic review must implement a detailed and reproducible framework for categorizing and evaluating all relevant literature (Zhou et al., 2015). Considering the specificity of the current research topic, a search solely dependent on generic platforms, such as Web of Science, PubMed, Scopus, etc., could be in sufficient. To successfully achieve the research objective, the authors decided to adapt a widely-used review framework (Ke et al., 2009; Yi and Chan, 2014). This framework delineates the review process into three phases to improve the study quality. The current study's review process is depicted in Fig. 1.

3. Data collection

3.1. *Phase 1*

A comprehensive search through the National Work Zone Safety Information Clearinghouse (NWZSIC) (https://www.workzonesafety.org/) and Transportation Research International Documentation (TRID) was conducted in Phase 1 using title, abstract, and keyword searches. TRID is a recommended database for transportation-related research (Avni et al., 2015). Transportation projects are considered part of the heavy civil industry. NWZSIC was selected to complement and augment the content found in the TRID database, where necessary. NWZSIC is a comprehensive database for work zone safety research, pulling information from approximately 500 sources, including state DOTs, universities, professional journals, such as Transportation Research Record (TRR) and those published by the American Society of Safety Engineers, American Society of Civil Engineers, Research Institutes, and so forth. Keywords such as "safety devices", "safety innovations", and "safety technology" were employed to identify candidate journal publications. As broad as it may seem, these keywords contributed to a comprehensive journal-centric search that identified 18 journals for articles related to the keywords search.

3.2. Phase 2

The findings from probing NWZSIC and TRID suggest that several high-ranked journals could be examined for useful information. Based on the findings from Phase 1, Phase 2 incorporated a cross-validation protocol using SCImago Journal and Country (SJC) Rank to streamline and identify journals to be included in the current study (Jamali et al., 2014). As a result, the authors were able to identify twelve journals with direct relevance to the present study: Accident Analysis & Prevention (AAP), Automation in Construction (AC), Institute of Engineering Technology Intelligent Transport Systems Journal (IET-ITS), Journal of Construction Engineering and Management (JCEM), Journal of Intelligent Transportation Systems (JITS), Journal for Safety Research (JSR), Journal for Transportation Engineering (JTE), Journal of Traffic and Transportation Engineering (English Edition) (JTTE), Journal of Transportation and Security (JTS), Safety Science (SS), Transportation Research Part C (TRPC), and Transportation Research Record (TRR). In addition, conference proceedings published by the American Society of Civil Engineers were included in the research scope. A title, abstract, and keyword search using more concise words was conducted to identify relevant articles within the nine peer-reviewed sources. The keywords used were: "work zone safety technology evaluation", "work zone safety technology assessment", "work zone safety technology effectiveness", "work zone safety technology testing", "work zone safety technology performance", "work zone safety innovation evaluation", "work zone safety innovation assessment", "work zone safety innovation effectiveness", "work zone safety innovation testing", "work zone safety innovation performance", "work zone safety device evaluation", "work zone safety device assessment", "work zone safety device effectiveness", "work zone safety device testing", and "work zone safety device performance"

In total, 6510 publications were located from the target journals. Cogent reasons for the enormous number of publications related to the searched topic are the possibilities of overlapping hits and the presence of articles not directly relevant to the research. A more refined search was conducted applying general criteria such as a study must focus on worker safety, be connected to a highway work zone, and be performance-based assessment. This refined search yielded 209 publications. Following a close inspection of identified publications, 62 publications were excluded due to lack of scope-fit. For instance, some authors reviewed the effectiveness of varying speed limit technologies without considering work zone applications (Abdel-Aty and Yu, 2013). Therefore, Phase 2 of the research process identified 147 journal articles and conference proceedings useful to the current study. Although 147 publications were identified through the examination of select journals, it was important to ensure that all published research within the selected domain were captured prior to analysis. This concern is assessed in Phase 3.

3.3. Phase 3

Though NWZSIC and TRID were utilized as primary databases for identifying publications during Phase 2 based on recommendations by Avni et al. (2015), the authors opted to verify the coverage extent of the database. The authors conducted a validity search using Science Direct, Scopus, and Web of Science databases. The secondary validation indicated that all journals and publications pertinent to the study were already included. Based on the 100% overlap rate between the primary and secondary database search, the researchers concluded that NWZSIC and TRID effectively covered publications related to work zone safety technology. Therefore, the final review was based on 147 articles in total. All candidate publications were evaluated and coded according to paper title, journal title, publication year, state, and country from which the publication originated (refer to Appendix A).

It is important to note that while the present study focuses on articles published in selected journals and conference proceedings, several DOT reports on WZST evaluations can be identified within current literature. The primary reason the authors excluded those reports is that most journals and conference proceedings included in the present study were by-products of published DOT research studies (reports).

4. Data analysis

This section presents the results derived from the analysis and categorization of the articles identified using the review framework.

4.1. Trend in work zone safety technology

4.1.1. Number of publications by year

Although research on WZST emerged in the late 1980's, the publication of findings in journals and conference proceedings gained momentum after 1996 (Fig. 2). The seminal study conducted by the Strategic Highway Research Program (SHRP) on work zone safety economic benefit research in 1995 could be considered the catalyst behind this trend. The SHRP study enhanced the visibility of findings from the studies conducted. Prior to 2000, three publications on WZST evaluations per year was the highest rate. Between 2000 and 2010, the number of evaluation studies increased approximately 270%. The increased interest in using technology to improve worker safety over the past decade is not necessarily synonymous with work zone safety

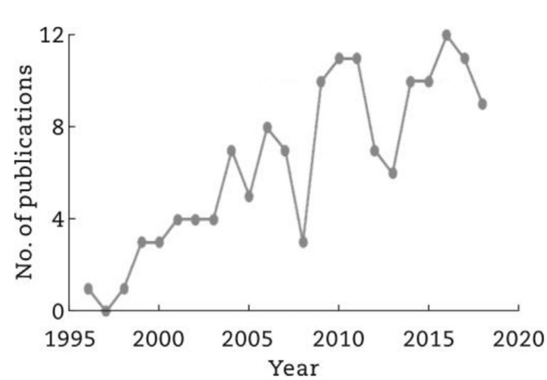


Fig. 2 – WZST publication trend.

Table 1 – Number of publications on WZST per journal/conference.

Journal	No. of publications
TRR	87
ASCEP	17
JCEM	8
JTE	8
JAAP	8
JTS	4
JSS	3
JITS	3
JIET	3
JTTE	2
JSR	2
TRPC	1
AC	1

Table 2 – Number of publications by country.

Country	No. of publications
USA	130
China	5
Australia	2
Italy	2
Japan	2
Belgium	1
Greece	1
New Zealand	1
Taiwan	1
UAE	1
UK	1

management. According to Zhou et al. (2013), publications related to safety management technologies in the building construction sector increased from 5 in 2002 to 19 in 2012, representing an increase of 280%. With the exception of 2008 and 2013, publications regarding the evaluation of WZST steadily increased over the years. The current study only includes publications through December 2018.

4.1.2. *Number of publications by journal/conference*

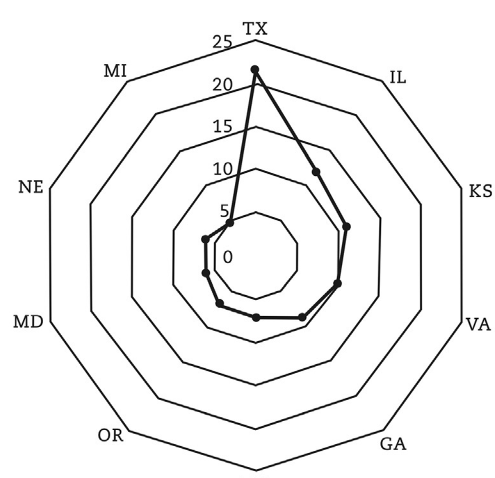
The numbers of publications based on each journal are listed in Table 1. Approximately 60% of publications pertaining to WZST evaluation were extracted from TRR. The observed skewness is expected, given that TRR is considered a primary source for publishing work zone related research (Avni et al., 2015). The next three sources contributed 33 articles. These sources are all published by the American Society of Civil Engineers.

4.1.3. *Number of publications by state and country*

Similar to Abudayyeh et al. (2004), publication country and state affiliations were determined based on the location of the institution conducting the study (in most cases, the location of the primary author). The amount of academic research conducted in a state could imply the level of interest and innovation within that state (Hong et al., 2012). As seen in Fig. 3, Texas is the most active state conducting WZST evaluation research. Although this could connote a high level of innovation or a large amount of resources devoted to WZST research, it could also be seen as a response to a dissatisfying statistic that places Texas as the state with most work zone related fatalities (BLS, 2018). Most publications analyzed in the current study were conducted in the US (88%), followed by China (5), while Australia, Italy and Japan have two publications (Table 2).

4.1.4. *Number of publications by technology*

The result from the literature review indicates that WZSTs were primarily evaluated through FHWA or state DOT sponsorships. Although not included within the scope of the present study, the type of WZST that was most evaluated was a portable traffic sign (PTS) in 1988. Evaluation studies in subsequent years covered a broad spectrum of safety technologies (Fig. 4). Between the years of 1995 and 2018, the most evaluated WZSTs were changeable message systems (CMS), speed enforcement systems (SE), warning lights (WL), and



GA: Georgia; IL: Illinois; KS: Kansas; MD: Maryland; MI: Michigan; MO: Missouri; NE: Nebraska; OR: Oregon; TX: Texas; VA: Virginia.

Fig. 3 – Number of publications by US states.

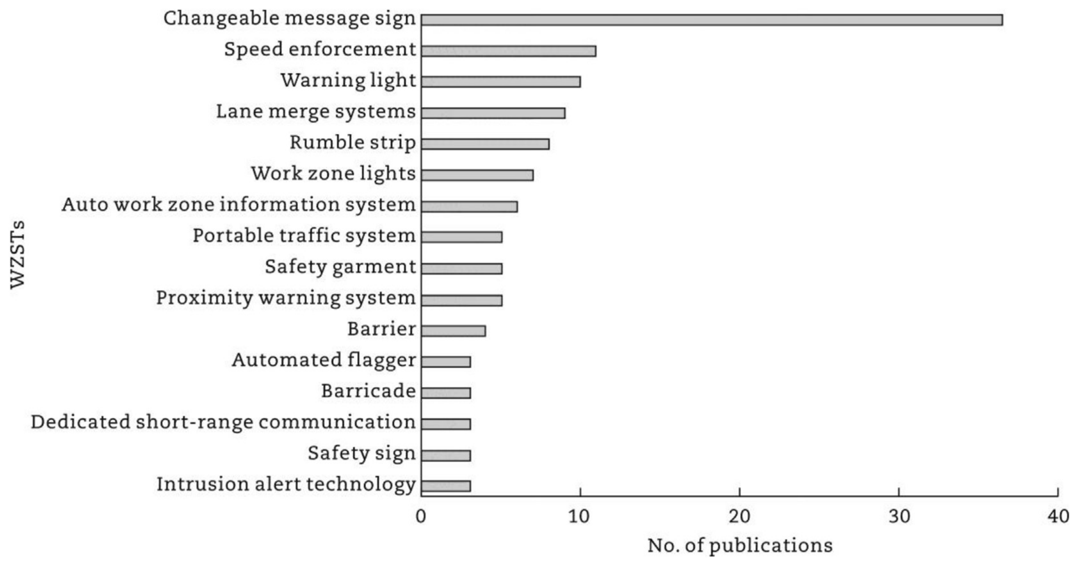


Fig. 4 – Number of evaluation studies for each technology.

lane merge systems (LMS). It is important to note that some publications evaluated more than one safety technology either independently or combined. Technologies independently evaluated in such studies are included in Fig. 4. Publications containing more than one technology are highlighted in Appendix A. Studies conducted on variable message systems and dynamic message systems are aggregated under CMS (Haghani et al., 2013). In addition, technologies designed to warn workers of imminent danger arising from close proximity to equipment are grouped as proximity warning systems.

4.2. *Review of current work zone safety technologies*

In order to evaluate the benefit of WZST currently in use, this section presents an in-depth discussion of technology's impact on workers. First, the authors propose to broadly classify WZSTs according to the following three categories. These categories are defined based on the objective of the WZST.

(1) Speed reduction systems (SRS): these technologies are used to reduce the traveling speed of motorists at advanced warning areas, transition areas, buffer areas, and work areas. The technologies could have direct or indirect physical impact on the traveling vehicle.
(2) Intrusion prevention and warning systems (IPWS): technologies set up to prevent errant drivers from intruding into a work zone and/or warn workers of imminent danger due to an intrusion into the work zone.
(3) Human-machine-interaction detection systems (HMIDS): these are technologies implemented inside a work zone to alert workers and equipment operators of an imminent collision between a worker and equipment.

These three categories were applied in the present study to create a collective and holistic assessment of findings from past evaluation studies.

4.2.1. *Speed reduction systems*

Past studies identified high vehicle speed as a primary cause of injuries and fatalities within construction work zones. According to Paaswell et al. (2006), inattentive motorists and high-speeds were major causes for errant vehicles entering the work area. Reductions in speed and speed variance have been attributed to fewer traffic accidents (Finch et al., 1994). In an effort to reduce the approach speed and speed within the work zone, several technologies have been proposed by manufacturers and tested by state DOTs on controlled sites and live projects (Debnath et al., 2012). Technologies such as drone radar and radar speed displays (Eckenrode et al., 2007; Jafarnejad et al., 2017; Streff and Molnar, 1995; Ullman, 1991) and speed enforcement systems (Benekohal et al., 2008, 2009; Fontaine and Carlson, 2001; Medina et al., 2009; Soole et al., 2013; Thomas et al., 2008) are implemented in highway work zones as enforcement measures (Debnath et al., 2012). Results from the referenced studies indicate that the vehicle speed reduction associated with the application of drone radar and speed enforcement systems ranges from 6.1% to 23.7%. In fact, a review conducted by Soole et al. (2013) concluded that speed enforcement systems produce substantial returns on investment through the reduction of economic and social costs associated with work zone accidents.

Multiple evaluation studies focused on informational measures were conducted by state DOTs, including CMS (Ahmed et al., 2016; Bai et al., 2015; Domenichini et al., 2017; Gambatese and Zhang, 2016; Huang and Bai, 2014), dynamic speed display signs (DSDS) (Ardeshiri and Jeihani, 2014; Mattox et al., 2007; Teng et al., 2004; Wang et al., 2003), and variable speed limit signs (VSL) (Edara et al., 2016; Kang et al., 2004;

Lin et al., 2004). Speed reductions ranging from 1 to 11 mph were reported by various authors across the various informational speed reduction technologies. For instance, findings from a study conducted by Fontaine and Carlson (2001) indicate that portable changeable message signs (PCMSs) could reduce motorist speeds by 10 mph.

Lastly, physical speed reduction measures were evaluated by various state DOTs, including versions of rumble strips (temporary/portable) (Elghamrawy et al., 2012; Fontaine and Carlson, 2001; Kang and Momtaz, 2018; Meyer, 2000; Sun et al., 2011; Wang et al., 2011; Yang et al., 2015) and warning lights (Finley et al., 2001; Sun et al., 2012) and temporary work zone lights (Bhagavathula and Gibbons, 2017, 2018; Hassan et al., 2011; Jafarnejad et al., 2018). Results from these assessment studies indicate that portable plastic rumble strips reduced average vehicle speeds by 6–14 mph while warning lights and temporary work zone lights significantly improved object detection distances (Bai and Li, 2011; Bhagavathula and Gibbons, 2017; Finley et al., 2014; Wang et al., 2003). However, glares from the warning and temporary work zone lights could impair driver's vision. Therefore, temporary work zone lights, such as balloon lights, should be aimed away from the perpendicular of the driver (Bhagavathula and Gibbons, 2017).

In certain cases, multiple speed reduction technologies were evaluated within one study. Results from multiple studies showed that combining more than one speed reduction technology could significantly reduce motorist speeds (Brewer et al., 2006; Fontaine and Carlson, 2001; Zhang and Gambatese, 2017). For instance, a combination of regulatory speed signs, PCMSs, and radar speed signs reduced vehicle speeds through the work zone by an average of 3.47 mph, while a combination of regulatory speed signs and radar speed signs had a marginal impact on speed (0.83 mph average reduction) (Zhang and Gambatese, 2017). According to Ravani and Wang (2018), implementing CMSs and police enforcement in a work zone had more impact on vehicle speed reduction (between 5.2 and 8.8 mph) when compared to using only CMSs (between 2.9 and 7.0 mph).

Generally, evaluation studies on speed reduction technologies mainly reported benefits such as significant motorist speed and variance reduction, increased productivity, improved driver experience within a work zone, improved comprehension of safety instructions, and improved perceived worker safety. Consistent with findings from the literature review by Debnath et al. (2012, 2015), enforcement measures remain the most impactful method for reducing vehicle speed within work zones. Regardless, certain studies such as Ahmed et al. (2016), Brewer et al. (2006), and McCoy and Pesti (2002) reported statistically insignificant speed reductions or inconclusive results. Therefore, it is imperative that DOTs assess the effectiveness of these technologies before and during implementation.

4.2.2. *Intrusion prevention and warning systems*

Exposure to live traffic is sometimes considered an unavoidable hazard on highway construction projects. Although traffic-related hazards cannot be completely eradicated, the degree of exposure can be reduced using several means and methods. Positive protection systems (PPS) are proactive engineering control mechanisms primarily used to minimize the impact of intruding vehicles. Effective PPS include concrete barriers, ballast-filled barriers, shadow vehicles, vehicle arrestors, guardrails, traffic control barriers, terminal end treatments, impact attenuators, sand barrel arrays, and truck mounted and trailer mounted impact attenuation (ATSSA, 2009, 2010). Various authors consider PPS to be an effective means of protecting workers in a work zone (Iragavarapu and Ullman, 2016; Patnaik et al., 2015; Tymvios and Gambatese, 2014; Ullman et al., 2007; Ullman and Iragavarapu, 2014). In addition to being effective at reducing the impact of an intruding vehicle, PPS could provide an injury cost savings to DOTs and contractors in the US of up to $1.1 million annually and a crash cost savings of $196,885 (Ravani et al., 2011; Ullman and Iragavarapu, 2014). However, the cost of implementing PPS could be a barrier to adopting these technologies (Nnaji et al., 2018a).

Intrusion alert technologies (IAT) are primarily designed to alert construction workers of a possible work zone breach by a motorist. The first phase of IATs were designed using infrared beams, microwaves, and pneumatic pressured tubes as triggering mechanisms (Burkett et al., 2009; Hatzi, 1997). More recent IATs, such as Sonoblaster, Intellicone, traffic worker alert systems, and advanced warning and risk evasion (AWARE), have been evaluated by a number of state DOTs (Awolusi and Marks, 2019; Nnaji et al., 2018b; Theiss et al., 2018). Results from evaluation studies indicate mixed findings on technology effectiveness. For instance, Nnaji et al. (2018a) indicates that IATs produce between 74 and 90 dB (dB) when triggered 50 feet away from the worker. However, Awolusi and Marks (2019) reported a lower sound threshold (62 and 70 dB) for the same technologies at a similar distance. The reaction time, the time it takes for a worker to hear or see the alarm, also differed significantly. A consistent limitation highlighted in these studies is the presence of false alarms. The authors reported that although intrusion alert technologies could improve worker safety, their inability to provide sufficient reaction times, persistent false alarms, excessive set-up times, and inaudible alarms, limit its perceived usefulness. Additional testing may be required to ascertain the utility and effectiveness of IATs before deploying these technologies in work zones.

Flaggers are often exposed to the inherent risk associated with approaching traffic. Past studies indicate that at least 20% of road worker deaths involve flaggers (Pegula, 2013). The primary objective of auto flagger, also known as automated flagger assistant device (AFAD), is to reduce flaggers' exposure to live traffic on temporary lane closures on two-lane highways using a remote controlled portable traffic control system (Finley, 2013). In addition, portable traffic signs (PTS) have been used in work zones to reduce flaggers' exposure (Debnath et al., 2017). Findings from a comparative study focused on evaluating the effectiveness of AFAD and PTS suggest that AFAD should be implemented on short-term stationary operations on narrow roadways given their smaller size (Finley, 2013; Trout et al., 2013).

Delineation devices (DD) are primarily used to provide a travel path for motorists passing through a work zone and separating workers from live traffic. By creating a separation between passing traffic and construction workers, DDs improve worker safety. For example, using DDs reduces vehicle speed in a work zone (Chitturi and Benekohal, 2005; Theiss et al., 2015). Frequently-used DDs include longitudinal channelizing devices (LCD), barricades, drums/barrels, and cones.

4.2.3. *Human-machine-interaction detection systems*

Struck-by or cut-in/between incidents, involving construction equipment and objects, represent 13.1% of all construction fatalities (OSHA, 2017). Approximately 57% of struck-by vehicle fatalities in construction occurred in work zones (Wang et al., 2018). Similarly, FHWA (2018) stated that construction vehicles account for 48% of struck-by incidents in work zones. This section presents different technologies that have been evaluated and adopted to assist in combating the disproportionate number of deaths caused by human-machine interaction in construction work zones.

Proximity warning systems (PWSs) are designed to produce an audible alarm in reaction to sensing a foreign object within close proximity of a piece of equipment (Fullerton et al., 2009; Marks and Teizer, 2012; Park et al., 2015; Ruff, 2006; Teizer et al., 2010a). PWSs are predominantly used in other industries such as underground mining, manufacturing, and the railroad industry to improve worker hazard awareness (Begley, 2006; Larsson, 2003; Ruff, 2006, 2007). Although some equipment is pre-equipped with built-in PWSs, attachable versions could also be obtained. Existing literature indicates that several design and pilot testing experiments have led to significant improvements in the efficiency of PWS collision prediction (Jo et al., 2017), blind spot detection (Teizer et al., 2010b), false alarm reduction (Choe et al., 2014), and prompt notification (Yang et al., 2018). Although Marks and Teizer (2013) proposed a unified method for evaluating PWSs, various testing methods were implemented in the reviewed studies. In short, PWSs were considered a viable option for reducing construction equipment-worker collision, in most cases.

Another type of PWS is a visual-based warning system (VWS), which is an alert technology that visually warns workers of an impending accident. In order to reduce fatalities associated with equipment backing into workers, a navigation-based visual warning system for guiding equipment operators was developed and tested. Results from the evaluation study indicate that the system can successfully identify the presence of workers within 1.5–2 m (distance) and 15–20 degrees (direction) using a tablet attached to the operator cab (Banaeiyan et al., 2016).

In certain cases, a technology could fulfill multiple objectives. For instance, DDs could simultaneously prevent intrusion (creating a distinct drive path for motorists) and be used as a speed reduction device (narrowing the drive path). DOTs and contractors may opt for technologies that serve multiple purposes, since they could generate more benefits. However, no study investigated the cost effectiveness and cost benefit of utilizing technologies with multiple applications.

Overall, the literature review indicates that there is a growing interest in the evaluation and use of WZSTs. This growth in interest is largely due to the high rate of fatalities in the work zone and increasing effectiveness of these technologies. Using these WZSTs is expected to create an additional safety protection for construction workers and motorists.

However, contractors are only required, by contract, to implement certain technologies in a work zone such as speed reduction devices and truck/trailer mounted impact attenuation. Technologies such as PWS and IAT are typically not required by state DOTs in traffic control planning (Gambatese et al., 2017). Rather, construction organizations optionally decide whether they would implement these technologies in construction work zones (Gambatese et al., 2017). Based on incident statistics within the activity area in a work zone, and the growing utility of HMIDSs and IATs, state DOTs should encourage the use of these technologies through contractual obligation.

5. Discussion

5.1. *WZST trends and evolution*

Despite a variety of technologies existing among current types of WZSTs, and the continuous technology evolution, approximately 68% of the analyzed publications focused on speed reduction systems (SRSs). SRSs consistently recorded a higher share of published work, regardless of period (decade, for instance) assessed. This finding is consistent with a previous study that highlighted contractors and DOT stakeholders' inclination towards implementing speed reduction devices such as CMS when compared to intrusion devices such as IAT (Nnaji et al., 2018a). Previous authors seem to emphasize speed reduction because vehicle speed and speed variability have a great potential impact on accidents. It is believed that by reducing average transiting vehicle speed, rates of accidents in the work zone can be reduced significantly. Speed reduction is considered a proactive means of protecting both the worker and the motorist, thereby eliciting reasonable support from funding agencies such as the FHWA. Primarily, past studies on speed reduction focused on the evaluation of CMS, RS, and SE. However, in recent years, research studies focused on HMIDS and IPWS such as proximity detection systems and IAT have increased significantly (Fig. 5). This increase could be attributed to recent statistics that suggest that most construction fatalities are caused by construction worker–equipment collision, while about 50% of worker fatalities are caused by vehicle intrusions (CDC, 2016). Although the number of publications on proximity detection systems has increased, the number of actual market-ready products is limited. This discrepancy is largely because most of these technologies are currently being evaluated for effectiveness.

5.2. *Application of smart work zones*

Findings from the present study suggest that there is a growing interest in the application of smart work zone systems in highway construction. Smart work zone systems are automated, reliable, portable, and interconnected devices that provide real-time travel conditions to the motorist (Pant, 2017). These dynamic management systems are designed to enhance work zone safety and mobility using estimation algorithms, sensors, and traffic management strategies (Li et al., 2016). Results from several studies indicate that smart

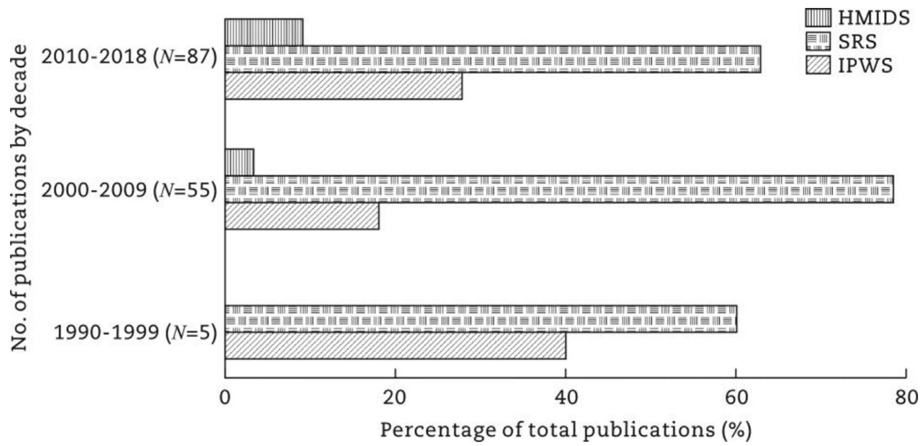


Fig. 5 – Research emphasis and evolution between 1995 and 2018.

work zones have shown considerable positive impacts on worker safety through adequate queue management, speed reduction, effective lane merging, and other controls (Edara et al., 2013; Pant, 2017; Qiao et al., 2014). In addition, the Minnesota DOT developed an intelligent work zone toolbox that could improve the effectiveness of smart work zone system applications. This toolbox contains guidelines and implementation procedures for selecting the most effective smart work zone system for different applications (Li et al., 2016). Vehicle-to-infrastructure and vehicle-to-worker technologies could be integrated into smart work zones to improve safety of workers and motorists. Moreover, emerging autonomous technologies such as autonomous truck mounted attenuator and automated intrusion detection systems could be incorporated into a smart work zone system to enhance decision making around the work zone and provide workers with valuable real-time information.

5.3. *Relationship between WZST and fatalities*

Publication trends show that the number of studies focused on WZST evaluations has fluctuated over the past 25 years. At the same time, the number of fatalities in work zones has fluctuated as well. The trend depicted in Fig. 6 does not show a clear relationship between the level of interest and adoption of safety technologies and worker fatalities.

While the trend in evaluation studies is a better metric for measuring the level of interest in WZST (compared to the actual adoption of such technologies), an indication of interest is expected to translate to actual technology adoption (Davis et al., 1989). Nevertheless, increased adoption, implementation, and diffusion of technology have the capacity to reduce accidents since in most cases, technology applications can reduce worker exposure to high risk activities (e.g., implementation of AFAD). To verify the actual safety impact (fatality and injury reduction), future studies should evaluate the rate of adoption and diffusion of these technologies across the US and assess the impact of WZSTs using direct measure of effectiveness metrics, where possible.

6. Research gap and future work

6.1. *Lack of WZST financial implication studies*

Financial indices such as return on investment (ROI), cost-effectiveness analysis (CEA), and benefit-cost analysis (BCA)

Fig. 6 – Number of work zone fatalities (BLS, 2018) and WZST evaluation publications per year.

are important yardsticks that drive adoption and diffusion of technology (Fyhrie, 2016). As most WZSTs require significant investment, consumers (such as DOT's and contractors) need to determine the cost-effectiveness of the intervention prior to its implementation. Although a few studies assessed the BCA of some WZSTs, further investigation into developing robust ROI and BCA frameworks for WZSTs is required to ensure a holistic evaluation of technologies. From a consumer perspective, it is paramount that an acceptable ROI on capital purchases should be first realized to strengthen adoption of a technology. Given the level of influence that DOTs have regarding traffic control technology implementation, it is important that manufacturers have an academically developed and supported process for determining cost-effectiveness and benefit-cost, both of which are considered better measurements (from a societal perspective) than ROI (Chapel, 2016). For instance, contractors may be hesitant to implement a technology with positive benefit-cost ratios (or net benefit) and positive cost-effectiveness if the ROI is unattractive.

6.2. *Develop standardized (minimum acceptable) evaluation protocols for WZST*

Technology evaluation processes play a crucial role in the decision to adopt or reject a technology (Sinfield, 2010). Findings from the present study indicate varying evaluation approaches are executed for similar WZSTs. The lack of minimum evaluation requirements for WZSTs creates an avalanche of methodologies, which makes it inherently difficult to compare findings from similar studies. FHWA alongside state DOTs and other research institutions can provide a guideline that suggests the basic “must have” in every evaluation process to improve the quality of studies. Also, technologies such as intrusion alert technologies do not currently have an evaluation protocol (Fyhrie, 2016). It is paramount that as technology evolves and new products are proposed, evaluation processes, grounded in scientific rigor, are developed and disseminated.

6.3. *Develop a tool for optimal selection of WZST*

Although factors such as particular construction type, environment condition, and available resources play a vital role in regulating the use of WZST, the possible cost savings and improved efficiency derived from effective use of technology are worth investigating. A sparse collection of literature describes investigations of best-practices focused on the WZST selection process. For one, no study addressed how DOTs can effectively and efficiently combine safety technologies, drawing from their strengths while complementing weaknesses. Therefore, it is imperative that an integrated work zone safety analysis tool should be developed for assisting traffic engineers and planners in obtaining a clear understanding of the overlap between project constraints and WZST features. This analysis tool could be supported by a decision-making framework for selecting between technologies, which ensures less reliance on experiential knowledge. Reducing the reliance of bias-prone experiential knowledge and increasing the dependence on an academically proven, yet practical, process improves the quality of the decision. These tools will enhance the selection of proper interventions for improving work zone safety without significantly affecting work zone throughput.

6.4. *Encourage research on work zone vehicle-to-infrastructure and vehicle-to-worker communication*

According to FHWA, implementing vehicle-to-infrastructure (V2I) communication around work zones improves the accuracy of information transmitted to motorists (FHWA, 2017). Armed with more reliable travel time information, motorists could adjust traveling routes, thereby reducing the number of vehicles traveling through the work zone. Developing and evaluating different variations of V2I technology specifically for work zones should be encouraged. For instance, a technology that provides communication between motorist vehicles, construction equipment, and physical roadway infrastructure, such as signage, could improve safety in the work zone. During construction operations, construction equipment could impede the line of sight of vital information (direction, speed limit, etc.). V2I technologies could help reduce this problem by connecting construction equipment enabled with portable PCMS with physical infrastructure. The PCMS could relay the message that would have been unavailable to motorists without the technology present. Introducing technologies that inform vehicles of worker location in a work zone, and technologies that inform workers of potential vehicle intrusion (using machine learning algorithm, for instance, to predict driver behavior and potential outcome) into a work zone, could help improve worker safety.

6.5. *Lack of quantitative analysis tool for validating spending on safety technology evaluation*

Every year, the federal government makes funds available for conducting highway-related research. In 2016, the Federal Transit Administration (FTA) made $7 million available to demonstrate and evaluate innovative technologies with the potential to improve transportation safety (FTA, 2016). The sparsity of effective tools and methodologies that could be used by state DOTs to evaluate the singular or collective tangible (quantifiable) impact of financial investments on safety technology evaluation research should be addressed. Providing an effective framework for measuring the outcome versus research investment would verify the effectiveness of evaluation investment, thereby justifying possible need for more funds.

6.6. *Need to introduce more automated technologies in work zones*

Greater demand for and use of the state roadways by an increasing volume of traffic requires a greater amount and frequency of maintenance operations and potential exposure of workers to high-risk situations. The exposure of workers to work zone hazards and prevalence of crashes in work zones makes automating work zone operations imperative.

Automation technologies (ATs) can play a critical role in reducing the exposure of workers to dangerous operations. For example, automated striping vehicles, automated roadway pavement marker placement systems, automated cone placement and retrieval systems, automated flagging systems, and autonomous impact attenuation vehicles are examples of ATs currently available that could improve worker safety, work quality, and productivity. Effective application of automation, however, requires knowledge of the implementation needs and barriers to use. Future studies should focus on developing empirically supported literature on cost effectiveness, ideal specifications, implementation guidelines, and drivers and barriers to adoption and implementation of this class of technologies. Generating more insight on the utility of ATs will help drive the acceptance and diffusion of ATs.

7. Conclusions and limitations

Findings from the present study indicate that interest in the use of technologies to improve worker safety in highway construction is increasing significantly. To a large extent, the growing trend is due to the high level of fatalities in work zones and the perceived usefulness of safety technology implementation in these areas. In this study, 147 publications focused on WZST evaluation were identified and analyzed. The results from synthesizing these studies indicate that WZST has a positive impact on worker safety. Most studies were conducted in the US, while Texas conducted the most evaluation studies by state. In addition, the current study revealed groups of safety technologies in three main categories: speed reduction systems, intrusion prevention and warning systems, and human-machine-interaction detection systems. Results from the present study show that speed reduction technologies were the most predominant type of technologies evaluated. Specifically, CMS has been evaluated extensively across the US.

Despite the perceived usefulness of safety technologies within these categories, certain technologies have shown a below-par “technology transfer” as highlighted by the uneven distribution of research interest and lack of presence in certain states. In part, this perceived shortcoming could be attributed to the traditional nature of the construction industry. Furthermore, previous studies have emphasized that for a safety technology to be adopted in work zones, the technology should be easy to install and remove, durable, effectively transmit the message, reusable, and cost effective. Finally, based on the knowledge gaps identified, future research is suggested with a specific aim on the financial benefits of adopting safety technologies, implementation and evaluation of V2I and automated technologies, and development of decision-making tools.

Although a thorough systematic approach was applied to ensure broad coverage and inclusion of all target studies, there remains a possibility that some studies on WZST evaluation were overlooked. By limiting the review to articles published in certain journals and conference proceedings, it is likely some technologies discussed in DOT reports were not included. Also, some publications captured in journal databases not included in this study may have been omitted. However, given the rigorous process utilized in this study, it is expected that most technologies were captured. In certain cases, publication abstracts were analyzed rather than the entire publication due to access restrictions. Regardless of these limitations, the objective of the study was adequately met.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtte.2019.11.001.

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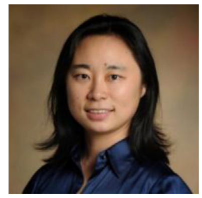

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